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RELIEF WELL SYSTEMS FOR DAMS AND LEVEES

By W. J. Turnbull, M. ASCE, and C. I. Mansur, J.M. ASCE

SOIL MECHANICS AND FOUNDATIONS DIVISION

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AMERICAN SOCIETY OF CIVIL ENGINEERS

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PAPERS

RELIEF WELL SYSTEMS FOR DAMS AND LEVEES

By W. J. Turnbull,[1] M. ASCE, and
C. I. Mansur,[2] J. M. ASCE

Synopsis

Excessive seepage and sand boils occur frequently during high water where dams or levees are underlain by strata of pervious sands and gravels. This paper presents the results of an investigation in which sand models were used to study: (1) The phenomena of underseepage; (2) the use of pressure relief wells as a means of controlling underseepage and sand boils along the lower Mississippi River levees; (3) the operation of relief wells; (4) well and seepage flows; and (5) landward substratum pressures with and without relief wells in operation, for various foundations, seepage entrances, and top strata. The conditions studied were those considered to represent qualitatively conditions commonly encountered in the lower Mississippi River valley.

Relief wells in the models, with proper spacing and penetration, effectively reduced excess hydrostatic pressure landward of levees or dams underlain by a pervious foundation for a wide range of seepage entrances, foundation conditions, and landward top strata. Seepage emerging landward of a levee without a well system was reduced materially with adequate well spacing and penetration, although the total underseepage flow was increased slightly. The model studies indicated the importance of insuring that the wells penetrate into the principal water-carrying strata in order to obtain efficient pressure relief. Borrow pits, excavated to sand, riverward of a levee, were found to increase underseepage and to have a pronounced effect on the design of a relief well system. Factors influencing the operation of the well systems in the models were: Well spacing, well penetration, seepage entrance conditions,

Note.—Written comments are invited for publication; the last discussion should be submitted by November 1, 1953.

[1] Chf., Soils Div., Waterways Experiment Station, Corps of Engrs., U. S. Army, Vicksburg, Miss.

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stratification of the foundation, depth and permeability of the pervious stratum, and characteristics of the landside top stratum. The diameter of the wells is known to be another factor which influences the performance of a well system, although the effect of well diameter was not investigated in this series of tests.

In addition to these factors that influence the design of a well system, there are other practical considerations that must be taken into account. Some of these are design of the well, maintenance of the system, corrosion, disposal of seepage, and degree of pressure relief or seepage interception desired. These factors were not a part of the model studies reported in this paper.

Introduction

Excessive seepage and sand boils during high water are common occurrences behind some sections of the levee system in the lower Mississippi River valley. Seepage and sand boils most commonly occur where the levees are founded on a thin top stratum of relatively impervious soils underlain by deep strata of pervious sands and gravels. Fig. 1 presents a generalization of this condition.

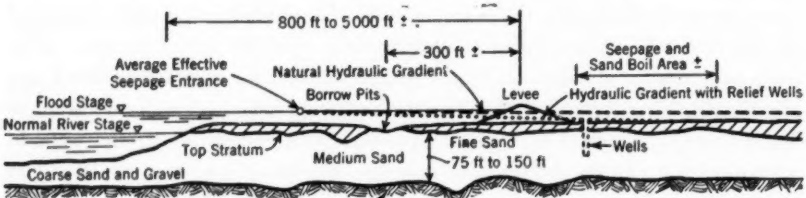


Fig. 1.—Cross Section of Geologic Strata and Levees

The use of relief wells for controlling underseepage beneath dams and levees has been investigated and a number of installations have been made during the period from 1941 to 1951. However, most of the theoretical analyses and model analyses made in connection with the design of pressure-relief well systems have been made for the case of a homogeneous pervious foundation overlain by an impervious top stratum with a vertical seepage entrance at some given distance from the line of wells. This paper presents the results of a series of model tests conducted to study the operation of relief wells for various generalized foundation conditions, seepage entrances, and landside strata, some of which are not covered by any presently available methods of analysis. A brief discussion of the conditions which cause sand boils also is included as are some of the considerations pertinent to the design of well systems for the control of underseepage.

Underseepage and Sand Boils

Sand boils and piping, landward of levees or dams, are the result of excessive hydrostatic pressures and seepage into and through pervious substrata

which provide for a communication of pressure and seepage from the river or reservoir to landside of the structure, as in Fig. 1. Under certain circumstances these conditions may produce subterranean pressures that become greater than the submerged weight of the top stratum at any locality landward of a levee or dam, and the excess pressure will cause heaving of the overlying soil. This may result in a concentration of seepage flow in the form of sand boils which may eventually cause failure by piping. Where the foundation and top strata are heterogeneous in character, as is usually the case, seepage tends to appear at localized spots instead of causing the entire top stratum to heave or become "quick." Such seepage may start a process of subsurface erosion or piping that may culminate in the formation of a passage, or pipe, beneath the structure without any heaving action. K. Terzaghi, Hon. M. ASCE, and R. B. Peck, M. ASCE, have stated that the mechanics of this latter type of piping defy a theoretical approach.[3]

Any tendency of the subterranean pressure to increase above the submerged weight of the top stratum only causes further expansion of the soil with increased percolation, thus creating a condition favorable for subsurface erosion. If such localized erosion is allowed to continue, piping may develop beneath the dam or levee. In general, continuous pipes rarely form through or under a levee, but their partial formation results in progressive collapse of the soil and accelerated erosion which may ultimately cause a blowout under the structure. Excess pressures in the foundation, where the top stratum over a pervious foundation directly under a levee is very thin, may also saturate the landside toe of the levee and cause the lower portion of the embankment to slough.

The extent of underseepage and excess hydrostatic pressure that may develop landward of a levee depends on the net head on the levee, location of seepage entrance, thickness and perviousness of the landside top stratum, and carrying capacity of the pervious substratum. If there were a completely impervious landside stratum overlying the pervious foundation and there were no flow of water landward, the hydrostatic pressure head beneath the landside blanket would equal the net head on the levee. This condition seldom exists, as there is usually some water flowing landward through the pervious foundation and upward through the surface stratum with a consequent landward decrease of pressure head, as shown in Fig. 1. This dissipation of head was observed in some of the models and partly explains why sand boils have not occurred in some areas where, without such head loss, subsurface pressures during high-water stages would have been sufficiently great to cause heaving or sand boils in the landside blanket.

Control of Underseepage with Relief Wells

The prevention of sand boils and the control of underseepage require some measure that will reduce excess pressure beneath the landside top stratum to a safe value and to control erosional seepage. One method of accomplishing this is to tap the underlying pervious strata with a properly designed series of

[3] "Soil Mechanics in Engineering Practice," by K. Terzaghi and R. B. Peck, John Wiley & Sons, Inc., New York, N. Y., 1948.

wells which will provide pressure relief and controlled seepage outlets that offer little resistance to flow and, at the same time, prevent erosion of the foundation soils.

The primary requirements of a relief well system for the control of excess pressures due to underseepage are the following:

1. The wells should penetrate into the principal water-carrying strata and be spaced sufficiently close together so as to intercept the seepage and reduce the pressure which otherwise would act beyond the wells.
2. The wells must offer little resistance to water flowing into and out of them; they must prevent infiltration of sand into the well after initial pumping; and they must resist the deteriorative action of the water and soil.

Relief wells offer several advantages as compared to gravel toes, pervious blankets, or other surface drainage measures where the foundation consists of stratified deposits of pervious materials, in that they penetrate into the more pervious strata in which pressure relief is necessary.

Theoretical Analysis of Relief Well Systems

A method of analysis frequently used in the design of relief well systems is one based on a mathematical solution by Morris Muskat.[4] Mr. Muskat assumed an infinite line of equispaced wells completely penetrating a uniform, semi-infinite, pervious stratum overlain by a uniform, absolutely impervious top stratum and underlain by a horizontal impervious stratum. The seepage entrance was assumed to be a vertical plane parallel to, and at a given distance from, the line of wells. An analysis for the case of wells partly penetrating the pervious stratum has been accomplished by using electrical analogy models.[5]

The formulas for the generalized conditions assumed by Mr. Muskat and in the paper by T. A. Middlebrooks, A. M. ASCE, and W. H. Jervis, M. ASCE, are not always applicable to field conditions. For example, the landside blanket is usually slightly pervious, or in other cases the seepage may enter the pervious foundation through the top stratum or through open borrow pits riverward of a levee. In some cases the landward or downstream blanket may be of finite length as a result of landward borrow pits which extend through the top stratum, and in other cases there may be an impervious deposit which blocks the landward extent of the pervious foundation. Many combinations of conditions exist which cannot be covered completely by any single theory.

Approximate formulas for the design of well systems have been developed by Messrs. Middlebrooks and Jervis, R. A. Barron[6] A. M. ASCE, and P. T. Bennett,[7,8] M. ASCE, that permit taking into consideration some of the conditions described in the previous paragraph.

[4] "The Flow of Homogeneous Fluids Through Porous Media," by Morris Muskat, McGraw-Hill Book Co., Inc., New York, N. Y., 1937.

[5] "Relief Wells for Dams and Levees," by T. A. Middlebrooks and W. H. Jervis, *Transactions*, ASCE, Vol. 112, 1947, p. 1321.

[6] "The Effect of a Slightly Pervious Top Blanket on the Performance of Relief Wells," by R. A. Barron, *Proceedings*, Second International Conference on Soil Mechanics, Vol. IV, 1948.

[7] "The Effect of Blankets on Seepage Through Pervious Foundations," by P. T. Bennett, *Transactions*, ASCE, Vol. 111, 1946, p. 215.

[8] "Comments on the Design of Relief Wells," by P. T. Bennett, from "Conference on Control of Underseepage," Waterways Experiment Station, Vicksburg, Miss., 1945.

As indicated, the assumptions made in the previously described methods of analysis seldom are realized in the field. Therefore, the sand model tests to be described subsequently were performed not only to study the general uses of wells for controlling underseepage but also to obtain information for the design of well systems for various generalized foundation conditions not subject to the aforementioned formulas. The results of the model tests are not directly applicable to the design of any specific well system. However, the results obtained may be of use in a qualitative sense, and to some extent quantitatively, where theoretical formulas are not applicable, provided proper corrections are made for the conditions at hand and sound engineering judgment is exercised.

Purpose and Scope of Investigation

The general purpose of these investigations was to study the operation of relief wells with various well spacings and penetrations, and to observe well and seepage flows and landward pressures, with and without wells in operation, for different selected conditions. Specific purposes of the investigation were:

a. To obtain information on well flows and landward pressure for different well spacings and penetrations, and for various seepage entrances such as in a river bed or riverside borrow pits excavated to sand;

b. To determine the ability of a line of wells to intercept underseepage where the landside top stratum is not impervious and the initial landward pressures are low without relief wells;

c. To determine the increase of total flow caused by wells where there is a considerable amount of natural seepage without wells and the landside top stratum is not impervious;

d. To verify, where applicable, available design data obtained from theoretical and electrical model studies for homogeneous foundation conditions; and

e. To study the effect of stratification on the efficiency of a well system as regards well penetration.

Description of Models

Four sand models, designated A, B, C, and D, with different generalized foundation conditions were constructed and tested. Variables studied in these models were: Well spacing and penetration; river bank and borrow pit seepage entrances; impervious, relatively impervious, and no landside top strata; and stratification of the foundation. The foundation and seepage conditions studied were those considered to represent qualitatively conditions commonly encountered in the lower Mississippi River valley. However, the results of the tests are also considered qualitatively applicable to other similar conditions.

The model studies were conducted in a steel flume approximately 28 ft long, 4 ft high, and 3.5 ft wide, as shown in Fig. 2. One side of the flume was tapped at numerous points so that piezometers could be attached for measuring pressures beneath the top stratum and within the foundation. The other side of the flume was composed of plate glass ½ in. thick that permitted the use of fluorescein dye lines for tracing flow patterns.

The primary requirements for similitude of sand models are that the flow be laminar, the model be an undistorted geometrical reproduction of the prototype, and that the permeabilities of the various strata have the same ratio as the permeabilities in nature. The absolute permeabilities of the strata affect only the rate of seepage; they have no effect on the pressure distribution within the foundation.

Variable-elevation overflow funnels were used to control the elevation of the water riverside of the levee. Similarly, shallow pans or circular overflow

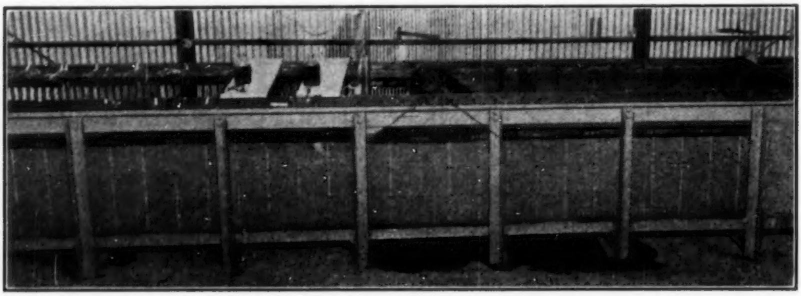
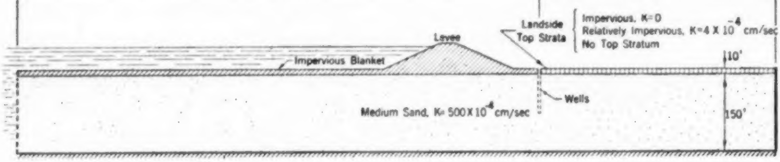


FIG. 2.—STEEL FLUME FOR MODEL STUDIES

weirs were used to maintain a constant tailwater elevation landside of the levee. The distribution of the hydrostatic pressure within the pervious substratum for the various test conditions was obtained from the piezometers previously referred to. The discharge from the wells and seepage through the landside top stratum were measured separately in model A.

All dimensions, well diameters and spacings, seepage and well flows, and head measurements in the models have been adjusted to prototype units in



MODELS A-a-1, 2, 3

Seepage Entrance at River

FIG. 3.—HOMOGENEOUS FOUNDATION, MODEL A

this paper. Well and seepage flows are given in gallons per minute per foot of net head, and hydrostatic pressures are given as a percentage of the total net head. All flow measurements have also been adjusted to a temperature of 20° C.

The relief well systems were simulated in the models by a series of wells near and parallel to the levee toe, spaced so that different well spacings could be obtained by plugging various combinations of wells. The wells were so

spaced that the sides of the flume always represented a plane midway between the wells, regardless of well spacing. The wells in the model consisted of copper tube riser pipe ½ in. in diameter and a monel or brass screen fully penetrating the pervious foundation. Various penetrations of well screens into the pervious foundation were obtained by plugging the lower section of the screens at the desired elevation.

Homogeneous Foundation—Model A.—The foundation, seepage entrance, and top stratum conditions tested in model A are shown in Fig. 3. Landside top strata simulated were an impervious top stratum (model A-a-1), a relatively impervious top stratum 10 ft thick with a coefficient of permeability approximately equal to 4×10^{-4} per sec (model A-a-2), and no top stratum (model A-a-3).

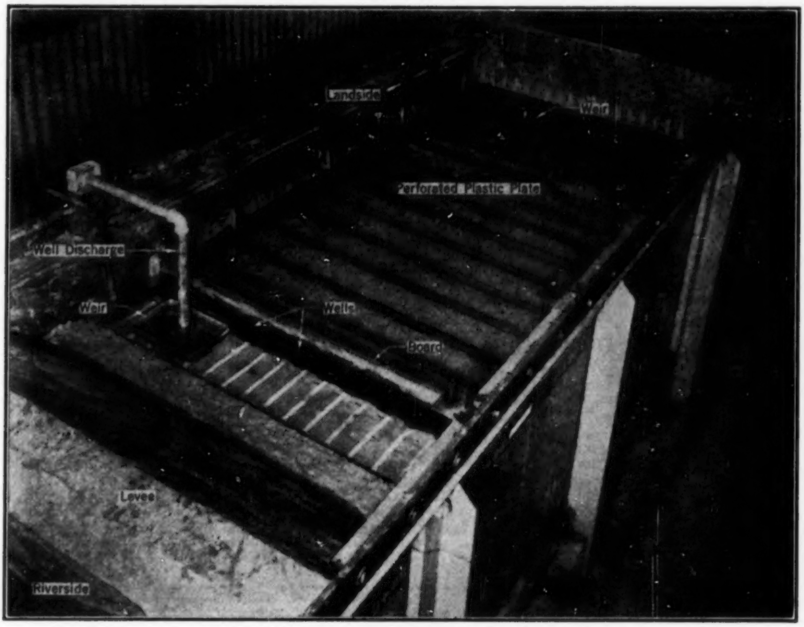
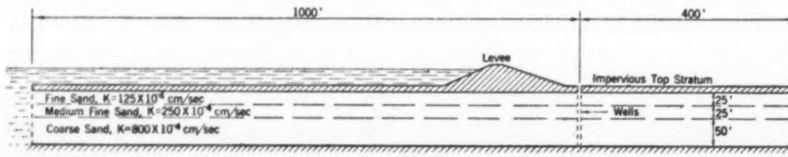


FIG. 4.—TEST CONDITIONS FOR MODEL A

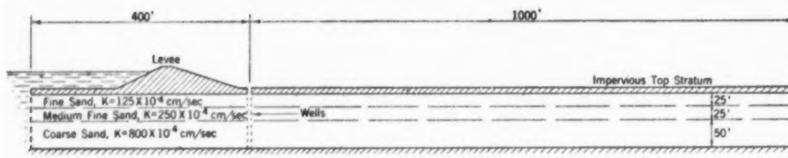
The relatively impervious landside top stratum of model A-a-2 was simulated by means of a plastic plate ⅛ in. thick perforated with 0.025-in. holes spaced on 2½-in. by 2½-in. centers. This landside top stratum, with no wells in operation, resulted in hydrostatic heads at the line of wells of 36% of the net head when the seepage entrance was at the river 1,000 ft from the well line. The sand used for the pervious foundation was a uniform, round-grained sand.

The arrangement of wells, landside top stratum, and overflow weirs for model A are shown in Fig. 4. Well penetrations of 25%, 50%, and 100%, and spacings of 23.6 ft, 43.3 ft, 86.6 ft, 130 ft, and 260 ft were tested in this

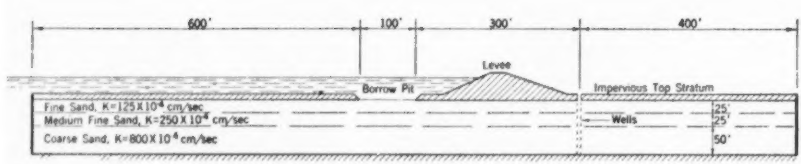
model. As seen in Fig. 4, flow from the wells was kept apart from the seepage through the landside top stratum by means of a board placed immediately landward of the well line. The tailwater at the wells and over the landside top stratum was maintained at the same elevation by the constant-level weirs shown in Fig. 4.



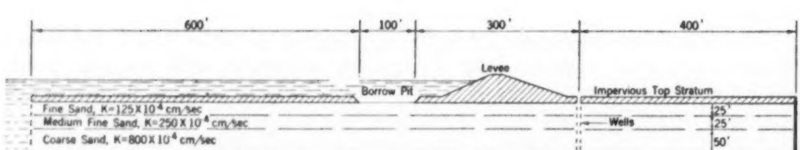
MODEL B-a
Seepage Entrance at River



MODEL B-aa
Seepage Entrance at River



MODEL B-b
Seepage Entrance in Borrow Pit Only



MODEL B-c
Seepage Entrance at River and Borrow Pit

FIG. 5.—STRATIFIED FOUNDATION, MODEL B

The 1:75 scale of model A resulted in the diameter of the ½-in.-diameter well screens being equivalent to an actual diameter of 3 ft. This well diameter is somewhat larger than normally used in actual practice, which is from 3 in. to 24 in., depending on the type of well and the diameter of the filter. The

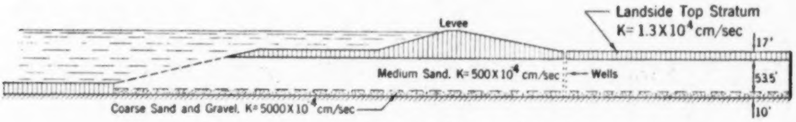


Fig. 6.—Greenville (Miss.) Levee, Model C

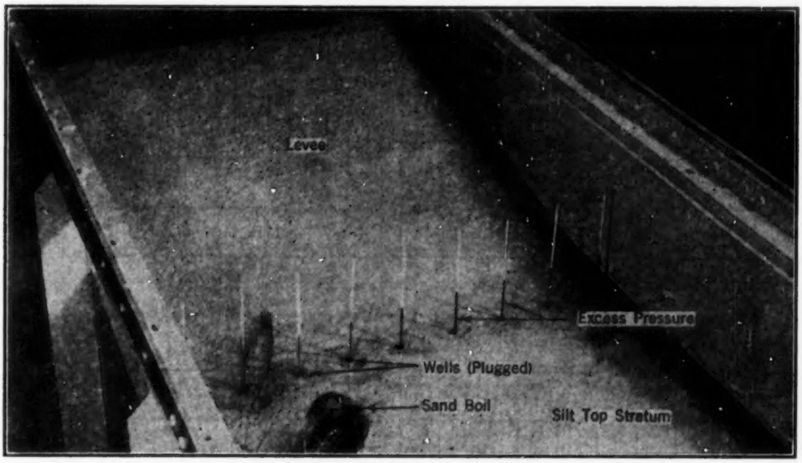


Fig. 7.—Measurement of Excess Substratum Pressures

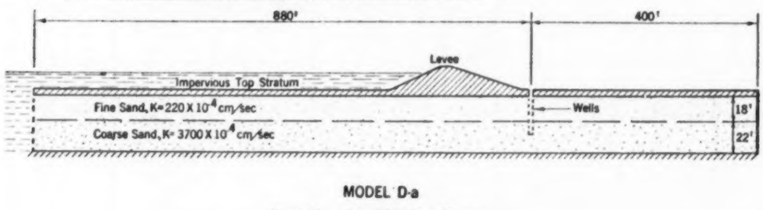


Fig. 8.—Memphis (Tenn.) Levee, Model D

diameter of a well does not affect the well flow appreciably when the diameter is greater than 6 in., but it does have an effect on the head between wells.

Stratified Foundation—Model B.—The foundation and seepage entrance conditions tested in models B-a, B-b, and B-c are shown in Fig. 5. This particular foundation was designed to simulate foundation conditions frequently encountered beneath Mississippi River levees. Model B had a scale

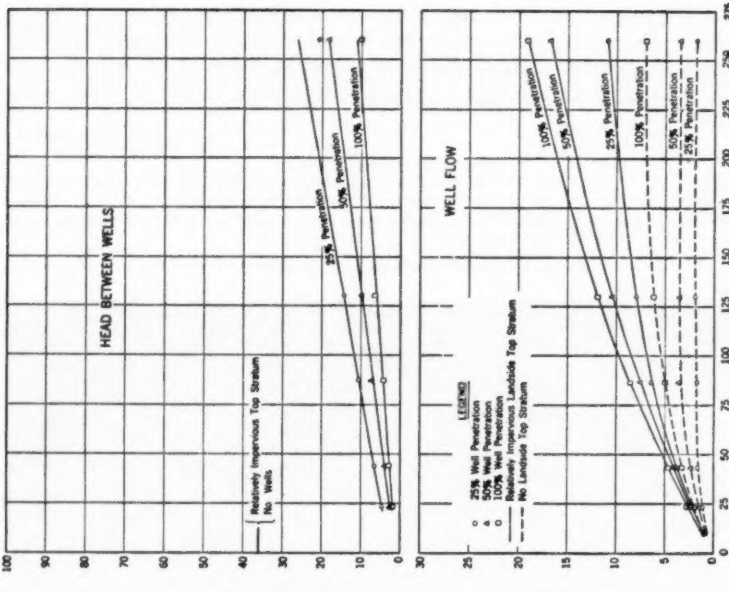


Fig. 10.—Flows and Pressures for Model A-a-2 and Model A-a-3

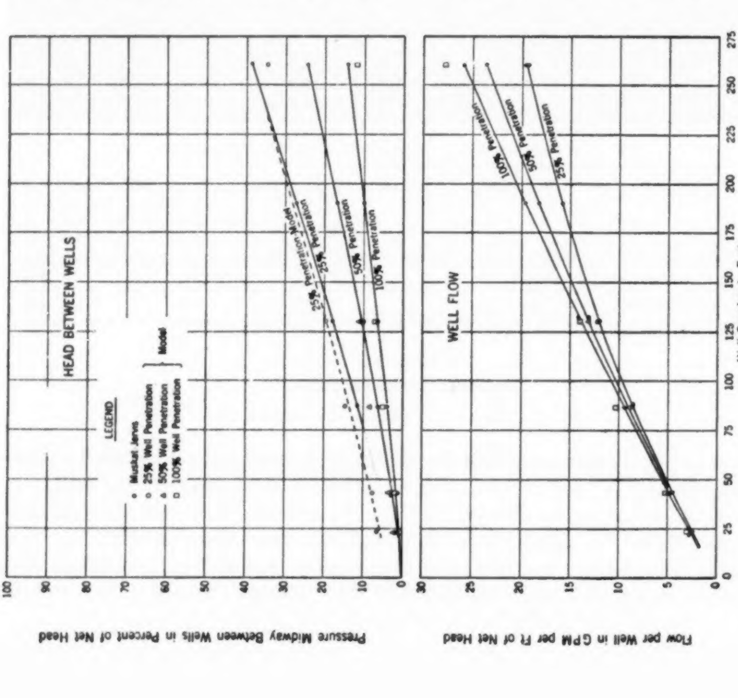


Fig. 9.—Flows and Pressures for Model A-a-1

ratio of 1:50 and well screens which corresponded to actual well diameters of 2 ft. The well penetrations and spacings tested in this model were 10%, 25%, 50%, and 100% and 29 ft, 58 ft, 87 ft, and 174 ft, respectively.

The primary purpose of model B was to obtain information regarding the effect of increased permeability with depth on the performance of partly penetrating wells, and the effect of riverside borrow pits, excavated to sand, on the design of relief well systems. The sands in model B had estimated permeability ratios of 1.0: 2.0: 6.4.

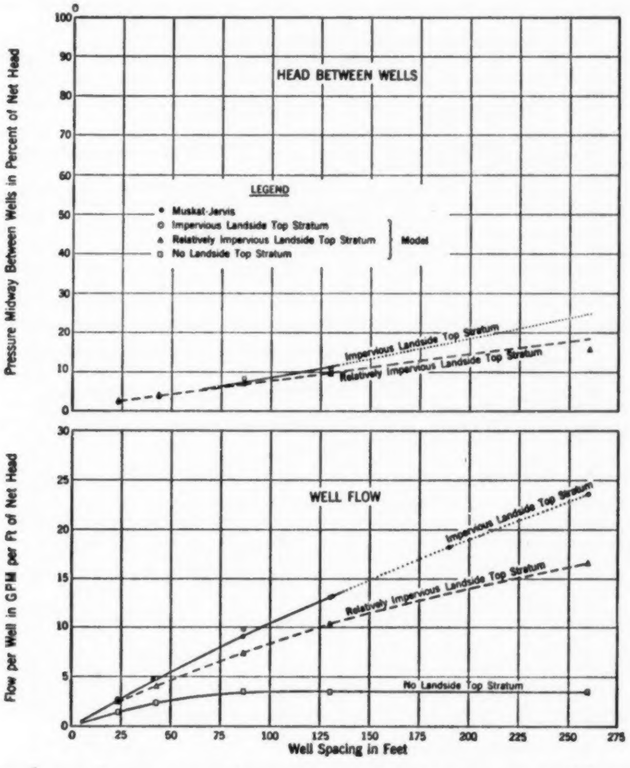


FIG. 11.—FLOWS AND PRESSURES FOR MODEL A-a WITH WELL PENETRATION OF 50% AND VARYING LANDSIDE TOP STRATA

Greenville (Miss.) Levee—Model C.—The foundation, seepage, entrance, and top stratum conditions tested in model C are shown in Fig. 6. Well spacings of 19 ft, 58 ft, and 174 ft were used with a well penetration of 100%. The scale of this model was 1:50 and the diameter of the well screens corresponded to an actual diameter of 2 ft. In order to measure the excess substratum pressures, piezometers were inserted in the plugged wells. This arrangement is shown in Fig. 7.

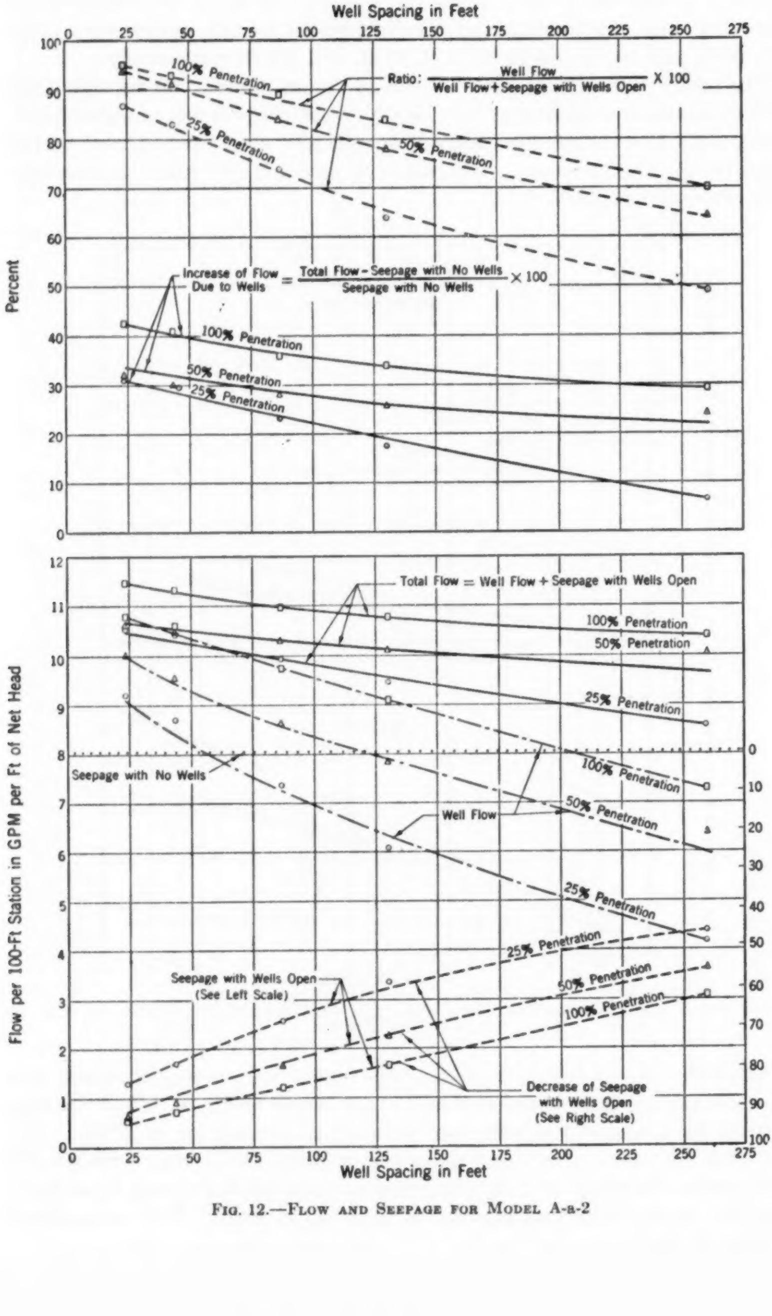


FIG. 12.—FLOW AND SEEPAGE FOR MODEL A-a-2

Memphis Levee—Model D.—Model *D*, shown in Fig. 8, was constructed to simulate certain levees in the City of Memphis, Tenn., that are founded upon relatively thin impervious surface formations underlain by pervious strata.

Tests were made with relief wells on various spacings and with different screen openings and penetrations. Well spacings of 19 ft, 43.5 ft, 58 ft, 87 ft,

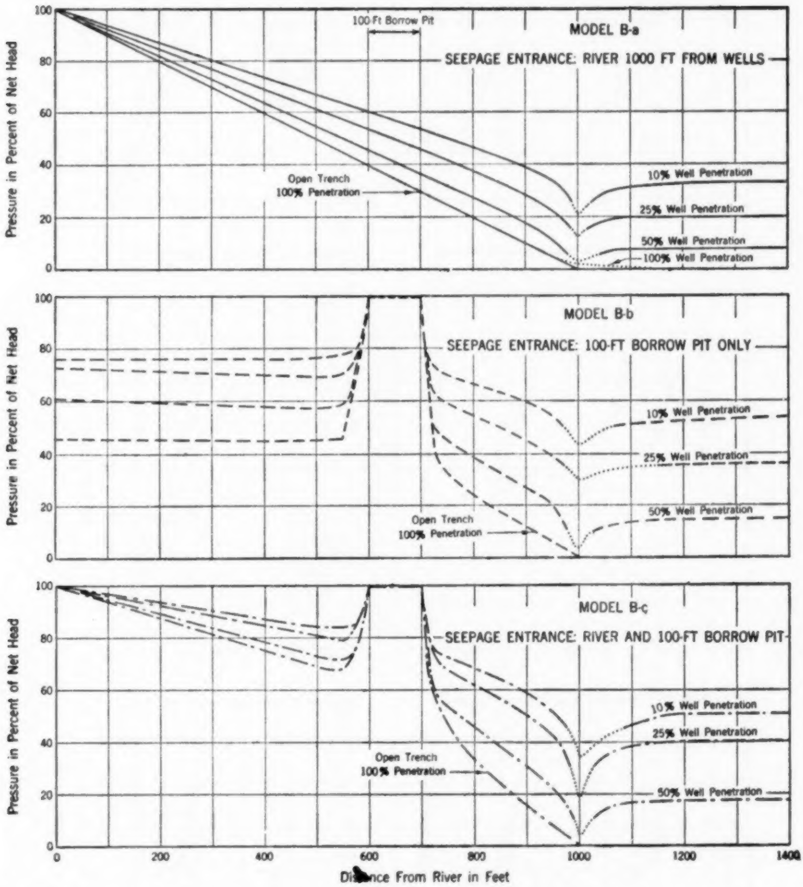


FIG. 13.—HYDROSTATIC PRESSURES BENEATH TOP STRATUM FOR MODEL B, WITH WELL SPACINGS OF 29 FT

and 174 ft were tested in this model. The scale of the model was 1:50 and the well screens corresponded to wells with a 2-ft actual diameter.

TESTS AND RESULTS

The test results obtained in models A, B, C, and D are shown in Figs. 9 through 19. The results obtained in the various models, as shown in the

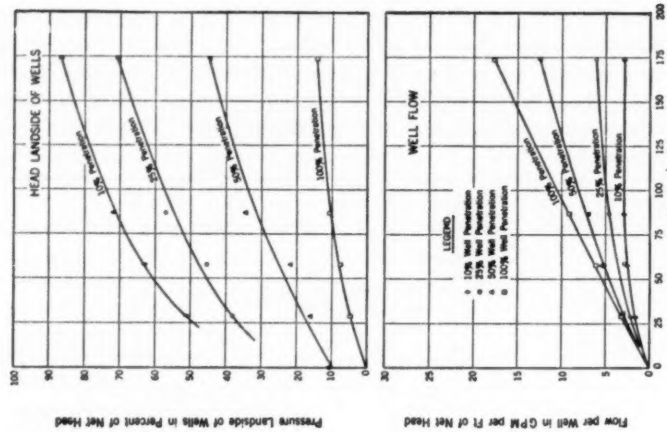


FIG. 16.—FLOWS AND PRESSURES FOR MODEL B-c

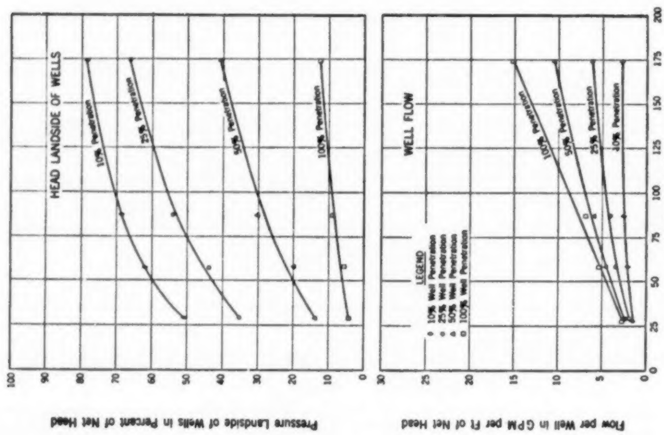


FIG. 15.—FLOWS AND PRESSURES FOR MODEL B-b

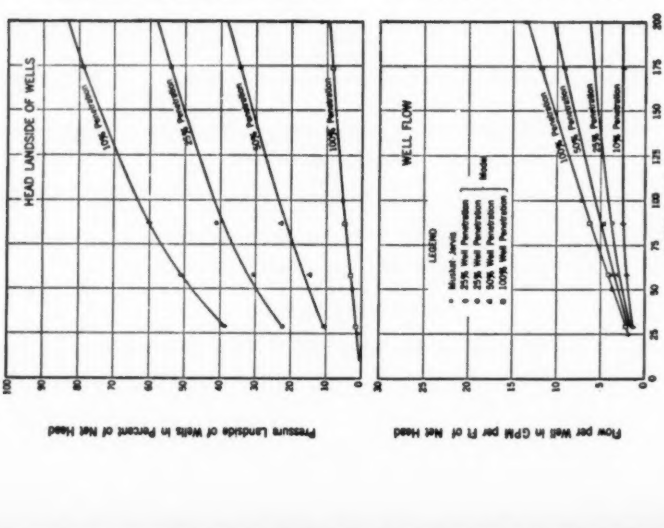


FIG. 14.—FLOWS AND PRESSURES FOR MODEL B-a

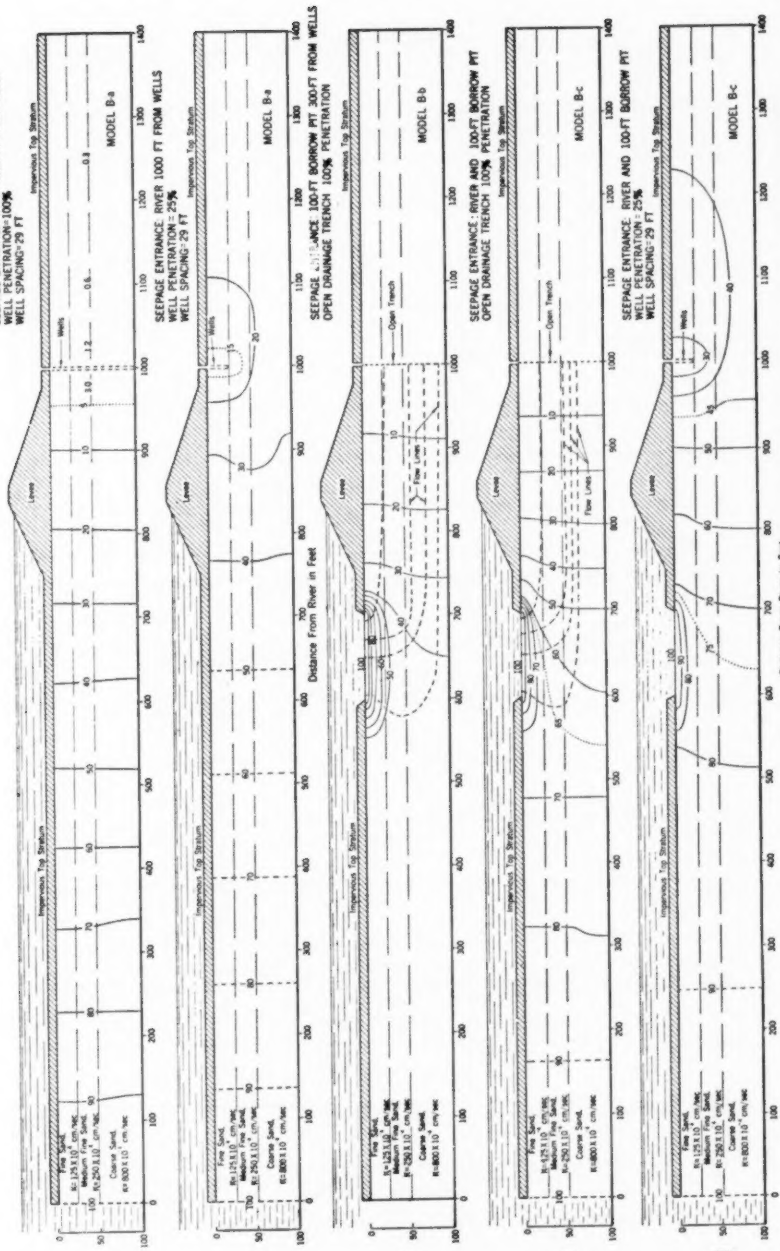


FIG. 17.—EQUIPOTENTIAL AND FLOW LINES FOR MODEL B

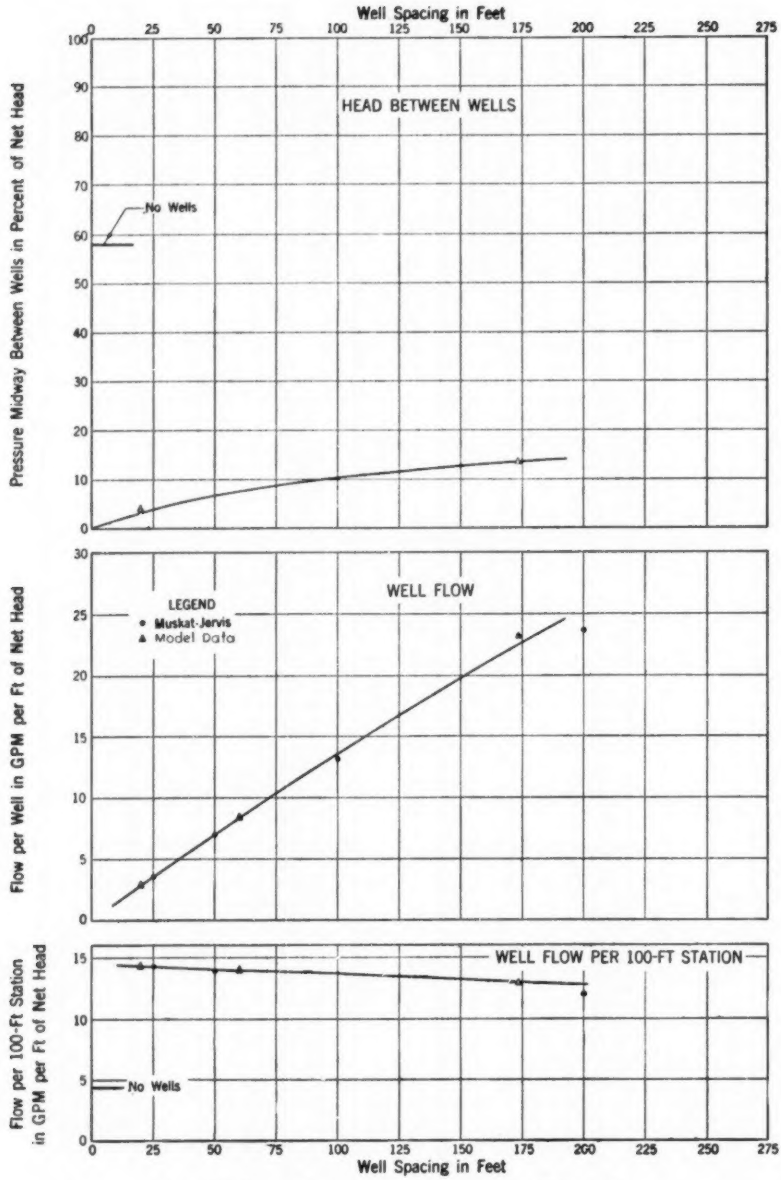


FIG. 18.—FLOWS, SEEPAGE, AND PRESSURES FOR MODEL C

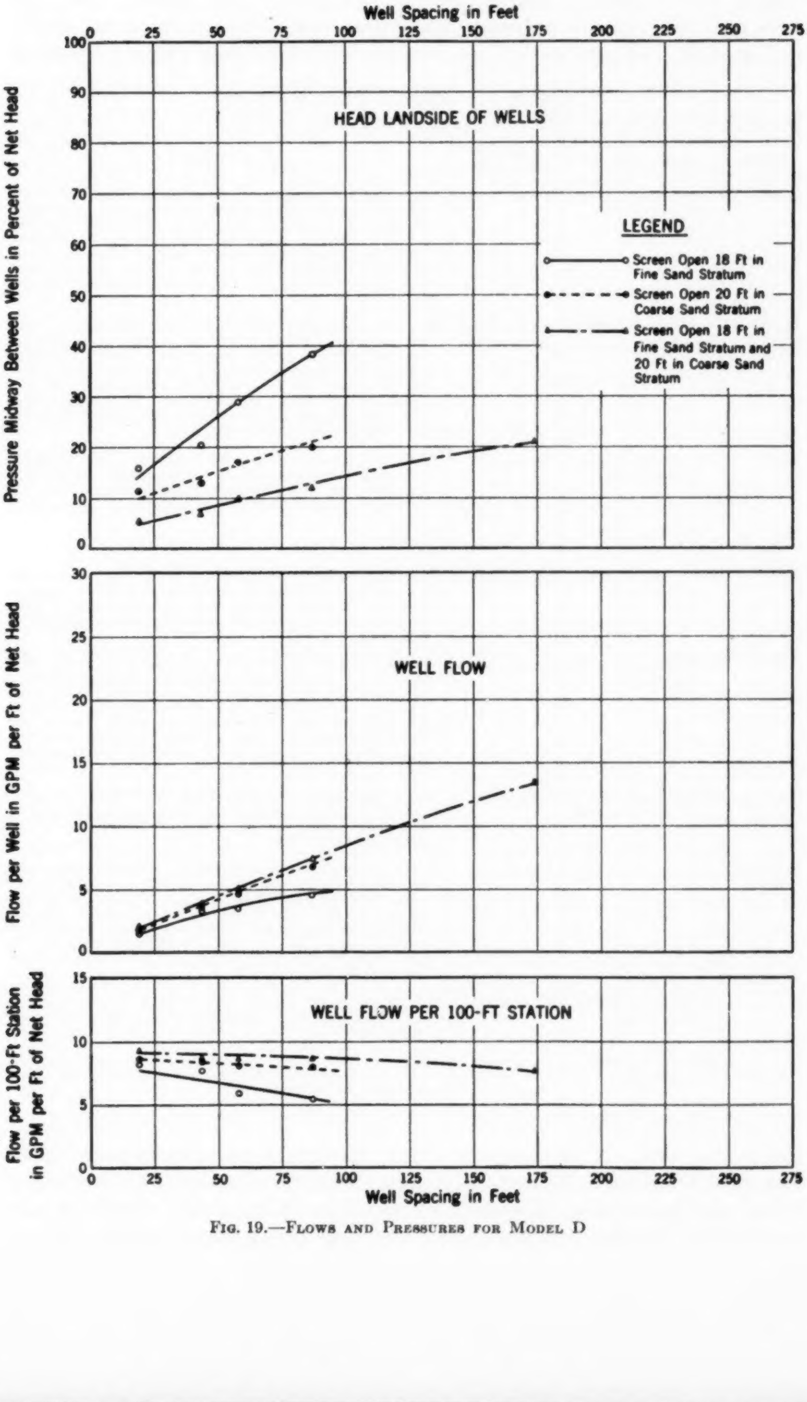


Fig. 19.—Flows and Pressures for Model D

figures, are in terms of prototype head (percentage) and seepage flow. All data regarding seepage entrance, foundation conditions, landside top strata, well spacing, and penetration are presented in each figure showing results of

TABLE 1.—MODEL TEST RESULTS

Model	Seepage entrance	Landside top stratum	Test results
A-a-1	River bank 1,000 ft from wells	Impervious	The landside pressure was reduced 90% with either of the following combinations of well-spacing a and penetration W (Fig. 5): $W = 25\%$, $a = 60$ ft; $W = 50\%$, $a = 125$ ft; $W = 100\%$, $a = 190$ ft. Well spacings of less than 200 ft and penetrations greater than 25% had relatively little effect on well flow per 100-ft station, but did have a significant effect on the residual pressure between wells (Fig. 9).
A-a-2	River bank 1,000 ft from wells	Relatively impervious	An excess pressure of 36% H at the levee toe with no wells was reduced to 5% H with a well spacing of 50 ft and a penetration of 50% (Fig. 10). Natural seepage through the landside blanket with no wells was reduced approximately 80% by wells on 85-ft centers with a penetration of 50%. For this case, wells increased well flow plus seepage with wells only 28% above the natural seepage with no wells (Fig. 12).
A-a-3	River bank 1,000 ft from wells	None	Wells with a penetration of 50%, spaced on 50-ft centers, reduced natural seepage by approximately 50%. For this case, the wells increased the total seepage only 3% more than natural seepage with no wells.
A-a-1, -2, -3	River bank 1,000 ft from wells	..	See Fig. 11.
B-a	River bank 1,000 ft from wells	Impervious	Wells fully penetrating the coarse sand stratum on 100-ft centers gave a pressure reduction of 95% H, whereas wells on the same spacing, but only penetrating the top 25 ft of fine sand, reduced landward pressures by 58% H (Fig. 14).
B-b	100-ft borrow pit only, 300 ft from wells	Impervious	A 100-ft borrow pit, located riverside of the levee, with the river at an infinite distance, permitted approximately 15% more seepage to enter the foundation, for the same drainage facilities, than entered the foundation in model B-a with the river 1,000 ft from the wells (Figs. 14 and 15). To obtain the same landward pressure reduction required closer well spacing for model B-b than for model B-a.
B-c	River bank and 100-ft borrow pit	Impervious	Where seepage entered the foundation at both river and borrow pit, well flows were increased approximately 50% over those where seepage entered the foundation at the river only (Fig. 16).
B-a, B-b, B-c	....	Impervious	Where the foundation is stratified, drainage wells must penetrate the principal water-carrying strata to reduce pressures effectively (Figs. 14, 15, and 16). For a comparison of the hydrostatic pressures beneath the top stratum for various well spacings and seepage entrance conditions see Fig. 13. For the effect of open borrow pits on the seepage flow pattern for the foundation simulated by model B, see Fig. 17.
C	River bank 600 ft from wells	Impervious	For the same well spacing and 100% penetration, drainage wells gave approximately the same pressure reduction for model C as for models A and B (Figs. 9, 14, and 18).
D	River bank 880 ft from wells	Impervious	As in model B, where the foundation is stratified, relief wells must penetrate the principal water-carrying strata to reduce pressure effectively (Fig. 19).

the model tests. A summary of certain important test results obtained in each model is given in Table 1. The data shown pertain only to the particular model and wells being discussed. Application of the model results to any specific field problem would require that proper consideration be given to any

change in well diameter and penetration, foundation conditions, seepage entrance, or top strata, from that tested in the model. The term "seepage" as used in the figures for model A is limited to the seepage or water rising to the surface through the top stratum landward of the line of relief wells.

The well and seepage flows for distances from the line of wells to the seepage entrance at the river other than 1,000 ft may be computed for various well penetrations and spacings for model A-a from the following formula based on a straight-line variation of head beyond 300 ft riverward from the line of wells to the river.

$$Q = \frac{112{,}500\ H\ K\ q}{q(s - 1{,}000) + 11{,}250} \quad \text{(1)}$$

in which Q is the well or seepage flow per 100 ft of the prototype levee in gallons per minute, H is equal to the net head in feet, K is the coefficient of permeability in feet per minute, q represents the well or seepage flow in gallons per minute per 100 ft of levee as determined from the model studies, and s denotes the distance from the line of wells to the river in feet, equal to or greater than 300 ft.

The hydrostatic head midway between the wells may also be computed for distances at which s does not equal 1,000 ft from the following formula:

$$P = \frac{150\ H\ (\%)}{0.0133\ q(s - 1{,}000) + 150} \quad \text{(2)}$$

in which P is the head in feet midway between wells, when s is equal to or greater than 300 ft, and (%) is equal to the percentage of head between wells as obtained for s equal to 1,000 ft.

Conclusions

On the basis of the model studies that were undertaken, it can be concluded that relief wells with proper spacing and penetration will effectively reduce excess hydrostatic pressures landward of levees underlain by a pervious foundation for a wide range of seepage entrances, foundation stratification, and landward top strata. The pressures between wells and the well discharges are always slightly less for a relatively impervious landside blanket than for a completely impervious landside blanket, since the impervious blanket contributes to pressure relief. Therefore, well flows and residual landside pressures for relatively impervious landside blankets will be less than those computed for an impervious landside top stratum.

Another conclusion that can be made is that, with adequate well spacing and penetration, seepage normally emerging through a relatively impervious top stratum landward of a levee without wells may also be materially reduced, although the total of well flow plus seepage with open wells will be somewhat increased.

For the models tested and test conditions applicable, there was close agreement between the observed well flows, landside pressures, values computed from theoretical formulas, and electrical analogy studies.

Further study of the test results leads to the realization that it is important that the wells penetrate into the principal water-carrying strata, in order to obtain efficient pressure relief where the pervious foundation is stratified. The curves for partial penetration of Mr. Muskat and Messrs. Middlebrooks and Jervis are not applicable to this type of foundation. However, Mr. Muskat's formula for 100% penetration is applicable if the average horizontal permeability is used for computing the well flow.

Borrow pits excavated to sand on the riverside of a levee or dam increase underseepage and have a pronounced effect on the operation of relief well systems.

Finally, although the tests reported in this paper cover only certain specific foundation conditions, it is considered that the results obtained can, through the use of good judgment, be of use in designing well systems where conditions are generally similar.

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